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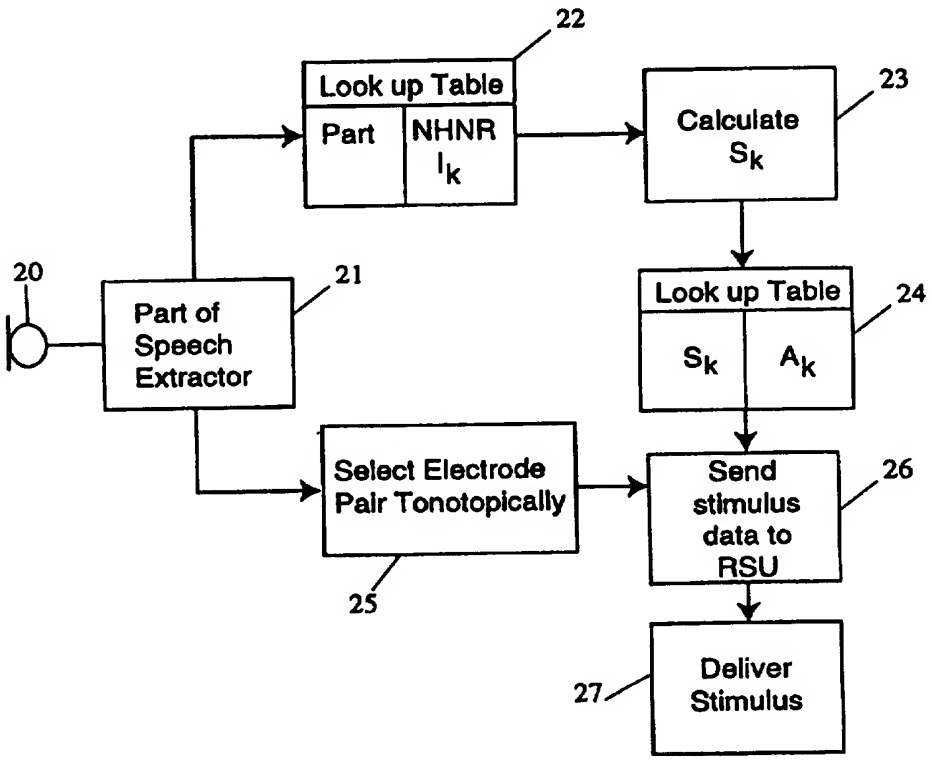
(54) Title: MULTIPLE PULSE STIMULATION

(57) Abstract

A stimulation strategy for cochlear implants is disclosed which seeks to approximate the time domain response of a patient's neural system to electrical stimuli, to the time domain response of a normal hearing person to a corresponding acoustic stimulus. Various implementations are disclosed.



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## Multiple Pulse Stimulation

### Technical Field

The present invention relates to methods and devices for providing electrical stimuli, and a strategy for electrical stimulation, for auditory prostheses such as cochlear implants.

### Background Art

Cochlear implants of various types have been proposed and constructed. For the purposes of explanation of the present invention, reference will be made to arrangements such as are commercially available from Cochlear Pty Ltd. However, it will be appreciated that the present invention is equally applicable to other types of auditory prostheses. An intracochlear electrode array is surgically implanted in a patient, together with a receiver stimulator unit for providing electrical stimuli to selected electrode pairs within the array. The receiver stimulator unit is connected, via an inductive transcutaneous link or a direct percutaneous connection, to an external sound processing device and microphone.

The present invention is concerned principally with the process of selecting appropriate stimuli, and with the actual stimulus pulses delivered in response to the acoustic stimuli. According to known arrangements, stimuli may be applied between different pairs of electrodes, to provide different modes of stimulation. In general, the electrode pair selected is related to the pitch of a detected tone. In this case, stimuli have generally used a consistent pulse timing and shape, and amplitude is determined by reference to the amplitude of the detected sound signal. It is also known to stimulate at a rate related to a detected tone, so as to induce a pitch percept.

However, it has been determined that the perceptions of patients in response to these stimuli are different from the perceptions using the normal hearing mechanisms. It has been determined that, in particular, the response of the auditory nerve to such stimulation is quite dissimilar to the neural response of a normally hearing person to the same sound.

In a paper by Parkins et al, entitled "A fibre sum modulation code for a cochlear prosthesis", Annals of the New York Academy of Sciences, 1983 at p

490, the authors discuss providing stimuli in such a way as to mimic the neural response of a normal hearing person to acoustic stimuli. The stimulus waveform is modified, using a complex mathematical model, so that the post stimulus time histogram approximates that of the normal hearing case. However, the arrangement described is not suited for real time processing so as to facilitate implementation in an implantable or portable device.

US patent No. 4495384 to Scott et al discloses a real time processing arrangement for a cochlear implant. This disclosure does not describe a system which accounts for the refractory period of nerve fibres, and as a result the stimuli produced do not provide a neural response having a time domain waveform similar to the normal hearing case.

In a paper by Motz and Rattay, (1988), "Signal processing strategies for electrostimulated ear prostheses based in simulated nerve response", the authors discuss the problems associated with hyperpolarisation of the auditory nerve fibres, and consequent loss of perception of higher formants by patients. The stimuli were simulated as if presented from a single electrode. The authors propose the use of further pulses after the initial stimulus pulse, the later pulses having considerable linear increases in amplitude, to improve the perception of higher formants. There is no disclosure of selecting pulses so as to produce a desired post-stimulus time histogram in the auditory nerve structures.

It is an object of the present invention to provide a practical arrangement for generating electrical stimuli so that an auditory nerve response is produced which better approximates the time domain response of the neural structures of a normal hearing person to a given acoustic stimulus.

**Summary of Invention**

According to one aspect the present invention comprises a cochlear implant device, comprising processing means for receiving an electrical signal corresponding to an acoustic signal, and stimulation means adapted to provide electrical stimuli to the cochlea of a human, said stimulation means including an electrode array comprising a plurality of electrodes operatively located within the cochlea, said device being arranged so as to permit selected electrodes to be provided with stimuli, said stimulation means being responsive to control signals

received from said processing means,

characterised in that said processing means processes said electrical signals in accordance with a predetermined instruction set, said instruction set determining the stimulation to be applied in response to the acoustic signal including the electrodes to be stimulated, the amplitude of the stimuli, and the timing of the stimuli, said processing means providing control signals to said stimulation means to cause said stimulation means to produce a set of stimuli, said set including for at least one electrode a first stimulus pulse and at least one further pulse within the refractory period of at least a substantial number of the nerve fibres stimulated by said first pulse, the set being selected such that the neural structures of a patient in response to said set have a time domain response which is an approximation to the time domain response of a normal hearing person to said acoustic signal.

The instruction set preferably analyses the electrical signal corresponding to the acoustic signal, so as to identify portions of the signal as corresponding to one of a group of predefined features. These may include, for example, phonemes, tones or chords. A look up table may be provided which provides stimulus sets which have been determined to operatively induce an appropriate time domain neural response corresponding to the acoustic feature. Alternatively, the neural response may be directly calculated. This stimulation is then presented via the electrode array.

The sets of stimuli may be selected so as to stimulate selected populations of nerve fibres at different times, so as to take account of the refractory period of the nerve fibres. The sets of stimuli may also take into account the responses of specific nerve fibres, and are preferably tailored to the responses of a particular patient. For example, each patient may have different degrees of array insertion, some electrodes may not be active post-operatively, and different patients have different degrees of nerve survival. The stimulus sets are chosen so as to allow the nerve response to the stimuli to approximate the time domain response of normal hearing patients to the respective acoustic stimulus. This response may be determined with reference to the post stimulus histogram, inter-spike intervals histogram, and/or the period histogram of

individual nerves, or of chosen bands or populations of nerves.

The stimulus sets may be designed in advance, using preferably a model of neural response and statistical and/or mathematical analysis. Alternatively, the stimulus sets may be calculated in real time. The stimulus sets may be calculated to take into account single unit effects, or population effects, or preferably both. The present invention allows tailoring of the stimuli, both for different acoustic inputs, and for the peculiarities of individual patients. It is believed that the closer the time domain waveform of the evoked auditory response via electrical stimulation can be brought to that experienced by a normal hearing person, the easier it will be for patients to interpret the precepts produced.

**Brief Description of Drawings**

The invention will be described with reference to the accompanying drawings, in which:

Figure 1 illustrates schematically an aspect of the theoretical basis fro the present invention;

Figure 2 illustrates in block form processing according to the present invention;

Figure 3 illustrates graphically theoretical and measured plots of spike rate against stimulus function;

Figure 4 illustrates a sample period histogram of a population of nerves;

Figure 5 illustrates a multiple pulse histogram according to one embodiment of the present invention;

Figure 6 illustrates a histogram produced according to standard techniques;

Figure 7 illustrates a histogram according to an embodiment of the present invention;

Figure 8 illustrates current levels required to produce the output of figure 5;

Figure 9 illustrates the spread of action potentials excited by the stimulation;

Figures 10 and 11 illustrate further implementation of the present

invention in block form; and

Figure 12 illustrates schematically a cochlear implant system;

Figure 13 illustrates the time and power signals associated with a phoneme;

Figure 14 illustrates firing probabilities for various bands of neurons;

Figure 15 illustrates the probability of spikes in various time periods for a particular selected band; and

Figure 16 illustrates a sample refractory function.

**Description**

The present invention relates to a broad principle for applying electrical stimuli to patients with acoustic prostheses. It is emphasised that whilst the present invention is described with reference to a specific implementation, a wide variety of possible implementations exist. For example, different models for neural response may be used to estimate the required stimuli, and different stimulation arrangements, for example percutaneous connection, may well be used.

A cochlear implant system of the type contemplated comprises in general terms a microphone 1 which receives sound signals and passes a corresponding signal to the speech processor 2. The speech processor processes the received electrical signal to produce a set of stimulus data. This is transmitted, together with power, from the external coil 3 to internal coil 4, and then to the receiver stimulator unit (RSU) 5, which then provides stimulus pulses to the selected electrode pairs of electrode array 6 so as to stimulate the nerve fibres and provide a percept of sound to the user.

The neural response cannot be derived as a trivial function of, say, the input sound signal. One aspect of the difficulty of accurately simulating the response relates to the complexity of the system. The normal hearing ear has approximately 30, 000 nerve fibres, each of which can reach action potential independently of the others at any time during the stimulus. It is not possible to generate electrical pulses which cause this system to behave identically to the normal hearing situation.

One aspect of the implementation of the present invention relates to

varying the numbers, amplitude, shape and rate of the pulses to evoke an approximation of the NHNR. This is achieved in particular by evoking the correct number of action potentials (counted across either one representative fibre, or alternatively across the population of fibres) within each "phase" of the waveform, or averaged over many appropriately chosen phases of the waveform. This phase corresponds to the available divisions within the stimulation period, which is limited by the modulation rate - if the modulation rate was 4 times the frequency of a tone, then each "phase" would be one quadrant of the waveform. This results in a "staircase" approximation to the NHNR which is very similar to that of the acoustical case. The specially designed stimuli are applied across each period of the simulated tone, and are designed via computer simulation, and mathematical analysis, of the auditory nerve's response to both auditory and electrical stimulation.

Modifications to the waveform are used to improve the spatio-temporal neural response. These modifications include (but are not limited to) modifications to the number, amplitude, spacing, and width of the pulses to better simulate the spatio-temporal pattern of the NHNR. These degrees of freedom are provided in conventional systems, but are generally not exploited.

The present invention allows for various types of temporal response to be induced, as is required in various applications. One approach is to utilise the present invention to evoke as near an approximation as possible to the correct population per stimulus time histogram, by applying several pulses per stimulus period. The pulse amplitudes may be chosen so as to generate the correct number of action potentials in each part of the waveform. The pulse sizes may be chosen using various means, examples of which are discussed below.

A further aspect of the present invention is that by utilising the refractive properties of neurons, it is possible according to the present invention to provide stimuli such that different bands within the stimulation range of an electrode (SRE) fire at different times. This allows for the stimuli to evoke desired inter-pulse timings within each band, so that the phase relationship between the bands in normal hearing can be approximated. The size of the bands chosen may be selected, so that the band size may be selected to be that size which

provides the best percepts for the patient. This may be customised for each patient.

The present invention is described largely in the context of available implant systems, which utilise a standard biphasic pulse. Altering the pulse shape will necessarily alter the time domain response of the associated neural structures. The present invention is not limited in scope to the use of existing or standard pulse shapes, although clearly alternative pulse shapes will alter the details of the effects noted above.

In order to more fully understand the present invention, we will initially briefly consider its theoretical basis.In a conventional cochlear implant, the neurones of the auditory nerve are stimulated by application of a series of biphasic currents between electrodes of the electrode array. Each biphasic stimulation causes a group of neurones to fire. The number of neurones that fire due to a stimulation is determined by such factors as relative location of the group of neurones to the stimulating electrodes, and the history of stimulation of those neurones. If many of the neurones are in a refractory period due to past stimulation then the application of new stimulation will not cause as many of them to fire as would be the case if they were being stimulated for the first time.

It is further desirable according to the present invention to provide an estimate which is representative of the temporal response of the wider population of nerves, not merely those close to a single electrode. In order to overcome variations in neuron response due to location with respect to the stimulating electrodes, the neurones can be considered as divided into strips, each of which are assumed to contain neurones that are equally stimulated by the application of a given stimulus pulse. This is illustrated schematically in Figure 1. Neurones 12 in the region of electrodes 10, 11 are notionally divided into strips, labelled i, i+1, and so forth.

Suppose that a single biphasic stimulation is applied between electrodes 10,11, at various amplitudes, and the ith strip of neurones monitored. Whilst of course in practise any given pulse will stimulate multiple strips, it is assumed that this strip contains the neurones most responsive to the stimulating electrode. The stimulus function $S_k$ describes the neural response from the kth pulse. $A_k$ is

the amplitude of the kth pulse. It is possible to make up a table for each strip relating $A_k$ to $S_k$.

In practice the neurones are not stimulated by isolated biphasic pulses but by a series of stimulations. Each electrical stimulation will elicit a neuronal response from a single strip of neurones of $NI_k$ action potentials, where N is the number of neurons in that strip, and $I_k$ is the averaged probability of any neuron from that strip acheiving action potential during pulse k . It is known that the pulse in a series of stimulation pulses that elicits $I_k$ has the same amplitude as the isolated pulse that elicits $S_k$ where $S_k$ and $I_k$ are related by:

$$S_k \approx l_k \Big/ \left[1 - \sum_{w=k-(n+c)}^{k-1} l_w \gamma(k-w)\right]$$

Let the pulse period equal T. (n+c) is the length of the relative refractory period divided by T, , and $\gamma(k-i)$ is one minus the refractory function measured for time kT since the last action potential.

Therefore it is possible to generate a particular $I_k$ by determining Sk and then looking up the appropriate amplitude of the biphasic pulse $A_k$ to be applied.

So far it has been shown how to determine the amplitude of the biphasic stimulation to be applied in order to elicit a desired neural response $I_k$ in the ith stimulated strip of nervous tissue.

**Linking of Acoustic Signals to Neural Response**

Current speech processors used in cochlear implant technology rely on extracting significant features of speech. For example, using the SMSP process, electrical signals corresponding to received sound signals are processed by means of band pass filters, eg. 16, to provide a signal corresponding to amplitude in each channels. A selected number of said amplitude signals having the greatest amplitude, e.g.6, are used to modulate the amplitude of the stimulation pulse.

In order to incorporate the present invention into such a system it is necessary to calculate the $I_k$ which would arise in the normal hearing situation in each band wherestimulation is to occur. This $I_k$ may be calculated by use of

an approximate model of the cochlea and normal neuronal response. See for example Parkins et al "A Fibre Sum Modulation Code for a Cochlear Prosthesis", Annals of the New York Academy of Sciences, 1983 p490, or one of the many other published models.

The $I_k$ is then mapped to the appropriate $S_k$ by means of the equation above, and the map of $A_k$ to $S_k$ is used in order to determine the amplitude of the biphasic pulse to be applied. This process is described in figure 2 . An input signal 20 is processed by software 21 in order to extract a particular feature or set of features. This process may be a conventional cochlear implant type, for example SMSP or identification of formants. Alternatively, it may be a software process to recognise phonemes or similar features, such as discrete musical tones. The recognised feature is referenced via look-up table 22 to provide a desired normal hearing neural response, $I_k$, which corresponds to a percept of the feature extracted. $S_k$ can then be determined with reference to the equation above. An amplitude $A_k$ for each pulse can then be derived from look-up table 24. Simultaneously, according to this implementation, the input signal 20 is processed 25 so as to select an electrode pair for tonotopic stimulation. The stimulus is then determined 26 by combining the derived $A_k$ with the electrode site selected at 25, to provide a set of stimuli to electrode array 27.

The look up table may be provided using any conventional memory device. The first table stores the required type of patient percept, that is, the feature extracted ( e.g. a phoneme, or a tone), with corresponding normal hearing neural response patterns. The other input to the table is the required volume level of the perception. The output of the lookup table is a set of electrical stimuli which evoke the desired neural response. These are preferably calculated off-line via methods similar to those described above, and stored. This arrangement allows for a reduction in processor capacity, as it is not necessary for whole waveforms to be fully calculated.

The second lookup table 24 requires as input the width of the stimulation pulses, the rate of stimulation, and the desired stimulus function ($S_k$), and returns the amplitude $A_k$ of the stimulus required for this. The values for the lookup table may be obtained in a variety of ways . One approach is to use animal studies

with a variety of pulse rates at a variety of amplitudes and rates (for each pulse width). From the responses measured, the 's' function can be calculated.

Figure 3 lists the expected spike rates for biphasic pulses as a function of the S function (for given pulse rates and pulse width) versus the actual experimental results. The experimental results were obtained by putting in fixed width biphasic pulses at various pulse rates and intensities, and graphing the neural response rates. The theoretical values may be calculated as follows.

Assume the stochastic process describing the timing of the action potentials is a self exciting point process ( Snyder and Miller, 1991). Define the number of spikes (events) to time $t$ as $Nt$ ,then at any time $t$ , the time since the last spike equals $t - t_{Nt}$ . The intensity of the point process ( Snyder and Miller, 1991) is equal to $s(t)\, r(t - t_{Nt})$, where $s(t) \geq 0$ is a stimulus related function, depending on time ( determined by the properties of the neuron and also the signal presented to the neuron) and $r(.) \geq 0$ is a refractory function, which lowers the rate of action potential generation as a function of the time since last action potential. $r(.)$ is determined solely by the properties of the neuron, and possibly also by the type of stimulus ( electric or acoustic), and is independent of the size of the stimulus.

Consider a system where the s function is a set of identical pulses spaced at a period of T with the width of each pulse W being less than the dead time of the neuron. Let the refractory function $r(t - t_{Nt})$ be constant over the following regions :

$$r\left(t - t_{N_t}\right) = \begin{cases} 0, \; 0 \leq \left(t - t_{N_t}\right) \leq w \\ \alpha_n, \; nT - w \leq \left(t - t_{N_t}\right) \leq nT + w, \; 1 \leq n \leq (b - w)/T \\ 1, \; \left(t - t_{N_t}\right) \geq b \end{cases}$$

Define

$$A = e^{-\int_0^w s(\tau)d\tau}$$

A is the probability of there being no points assuming a Poisson rate of $s(t)$ during the pulse, and no refractory effects. $\alpha_n$ is the size of the refractive function, where the last action potential occurred n pulses ago. Define N as the smallest integer such that (N+1)T-W ≥ b. Then, the steady state average rate of neural firing equals:

$$R = \frac{(1-A)}{T\left(1+\sum_{n=1}^{N}\left[1-A^{1-\alpha_n}\right]A^{\sum_{j=1}^{n}\alpha_n}\right)}$$

The values for lookup tables which relate the S function to the electrical intensity, for given conditions, may then be derived. This may be done in a number of ways.

A relatively simple method involves simply measuring the 'S' function directly for a given pulse set up by measuring the neural response under a number of conditions of pulse rate and intensity.

For instance, from Figure 3, a pulse at an intensity of about 35 when presented at 200pps would equate to an S function of about 10, and increases in intensity will approximately relate to increases in S function in a linear plus offset relationship..

Alternatively, at 200pps, to produce an S function of, say 20, a stimulus intensity of about 40 is required.

Of course, further research may result in a more detailed representation of the relationship, but this simple initial approach provides a reasonable representation.

An alternate method of determination of the necessary current values for a given pulse rate and width would be to (with each patient) apply a series of

pulses at fixed rate and width, and determine the threshold and comfortable levels of current. Then, a second parameter which indicates the size of the effective 'S' function at each level could be determined either by masking studies, or alternately by experiments where such a parameter is changed, and the perceptual response noted, ie. a particular sound could be coded, and then repeatedly played to the patient, under the assumption of a given proportionality between the current intensity, and the S function. The proportionality which returns the 'best' response - either in terms of naturalness or in terms of signal discriminability, could be stored in the look up table.

Thus, in this particular implementation, there would be three parameters: a threshold and comfortable level current, and a scalar parameter relating the current intensity (at a given pulse rate) to size of the 'S' function. Note that this would need to be done for each electrode stimulation combination. (ie. monopolar on each, bipolar on each pair, etc).

It will be appreciated that the pulse timing may be determined in various ways, within the scope of the present invention. In a simple implementation, a constant pulse rate may be used for all electrodes. This rate must of course be much faster than the relative refractive period, typically 20 ms, and is preferably less than 1ms. A preferred implementation uses a pulse rate for each electrode such that the rate is an integral multiple of the characteristic frequency of the adjacent neural population.

Figure 10 illustrates in block form an alternative implementation of the present invention. In this case, the received acoustic signal is processed by a transducer, and then enters a filter bank with n outputs. Illustratively, this may be 6. For each channel, a model of neural response for that part of the neural structure is used to produce a normal hearing neural response (NHNR) for that part of the acoustic signal falling within the channel. The $S_k$ can then be calculated using the equation shown above. The $S_k$ can be related to $A_k$ in a look-up table, as previously discussed. This $A_k$ can then be used as the basis for an instruction to the RSU to stimulate the appropriate electrode pair at amplitude $A_k$.

Figure 11 illustrates a related implementation to figure 10. The distinction

is that for each channel output from the filter bank, FFT techniques are used to derive a fundamental tone. Using a similar process to that described in relation to figure 1, this tone is related to a NHNR via a look up table, the $S_k$ calculated, and the corresponding $A_k$ determined from a further look-up table. A stimulus instruction is then sent to the RSU based on the determined $A_k$, and the electrode site corresponding to the tone. This process may be performed for each channel, or for a selected set of channels, determined via the SMSP technique, which have the greatest amplitude.

Figures 8 and 9 illustrate the principle of the present invention. To cause a population response similar to that from a NHNR for a 1 kHz tone, we could apply a continuously repeating set of four μs biphasic pulses, where the amplitudes were in the ratio of 4,6.5,7,0, resulting in a neural response in the ratio of 10,24,10,0. This is illustrated in figures 8 and 9.

The stimulation strategy proposed according to the illustrative example below is designed to be capable of implementation on a speech processor for cochlear implants which codes signals in terms of biphasic pulses. The examples illustrated utilise a fixed-width biphasic - bi-polar pulse, with an overall pulse width of 250us.

Figure 4 illustrates a population histogram for a population of 64 nerves around the 1 KHz place in a cat cochlea of total length 2.5 cm. The acoustic input is a 1 KHz tone. Figure 5 illustrates an approximation using multiple pulses according to the present invention.

Figure 6 illustrates output pulses using one pulse per period, in other words, using standard stimulation techniques. It is clear that such fixed-rate stimulation techniques can not form a close approximation to the desired output histogram at any frequency other than that of stimulation.

A multiple-pulse electrical stimulation model was iterated in a trial and error fashion until a set of current levels was found which provided the required histogram according to the present invention. The results can be seen in Figure 7. It is clear that for each period, the actual histogram closely resembles the desired approximation of Figure 5. Clearly, when compared to Figure 6, the present invention provides a much closer approximation.

**Example**

The following describes the implementation of the inventive techniques in relation to a specific sound input.

The phoneme /e (sounds like a short 'eh') is shown in figure 13,together with its power spectral density. Note that the spectrum has a number of peaks in the frequency spectrum (at about 800, 500, and 200Hz). These may be used as the main frequencies targeted for stimulation.The signal is from an isolated sound.

It was applied to the model from Benjamin D Brayant and John D Gowdy, "Stimulation of Stages I and II of Seneff's Auditory Model (SAM) Using Matlab", published in the proceedings of the 1993 Matlab User's Group Conference.

The model provides the averaged neural response for neurons from forty regions of the basilar membrane (ranging in characteristic frequency from high frequency to low frequency). Of course, the model could be set for any number of bands required, for example, the response of bands corresponding to each stimulating electrode. The response of some of the bands are shown as figure 14. It will be appreciated that other models and software could be used to produce this result.

The inventive technique may be used to code each band which corresponds to the characteristic frequency of neurons close to an electrode. For now, let us imagine that band 40 (for instance) corresponded to an electrode, and examine how the inventive technique could be used to generate pulses for that electrode. It will be appreciated that other electrodes would also be coded at the same time.

In the neural response here, there are two aspects. A broad lowering of probability over time, probably due to onset effects, as well as a fine structure. The present invention provides information to the user about both.

The fine structure of response here has approximately 20 periods in the 80ms, corresponding to a period of 4ms, or a frequency of 250hz. As an example, we will code with 8 pulses per period, requiring a coding frequency of 2000 Hz, or in other words a bin size of 0.5 ms.

The probabilities shown in the graph will be the $I_k$, or NHNR, of the theory

above. So using the formulas given, it is possible to work out the $s_k$ which will give the required responses.

Let us assume that the population of neurons we wish to control can be approximated by 3 approximately equally stimulateable regions (the centre one being the most stimulateable), and we want the total number of action potentials from this summed population (divided by the total number of neurons in the summed population) to follow the curve of the Figure.

Use the following equation,

$$S_{k,i} \approx l_{k,i} / \left[ 1 - \sum_{k-(n+c)}^{k-1} l_{w,i} \gamma(k-w) \right] \approx l_{k,i} / G_{k,i}$$

where $S_{k,i}$ is the stimulation function for the ith regionduring pulse k, $l_{k,i}$ is the averaging probability of neural response for the ith region during pulse k, and $\gamma(k)$ equals one minus the refractory function evaluated for the case where the last action potential occurred k.T ago

The probability of firing in each .5ms bin, can then be calculated, as shown in figure 15.

From this calculation, the probabilities required for the first 10 bins are:

| k | $l_k$ |
|---|---|
| 1 | .014 |
| 2 | .000 |
| 3 | .000 |
| 4 | .022 |
| 5 | .371 |
| 6 | .382 |
| 7 | .231 |
| 8 | .001 |
| 9 | .000 |
| 10 | .000 |

A given electrical pulse will elicit different responses at different distances from the site of stimulation. $\alpha_i$ is defined as the ration between a nominal S for some pulse, and the actual S generated for the ith region. Let us assume that the $\alpha_i$ for the three sub-populations are .7, 1 and .7 for each population (1, 2, 3).

Figure 17 gives approximate values of the refractory function( 1- $\gamma$), and the gammas would be (very approximately), about 1 for the first three bins (1ms), and decreasing from there to about zero after about 25ms (the 50th) bin. Therefore, responses from the last 50 bins are relevant when calculating the response in any bin.

So gamma will be approximately 1 for the first two bins, and .5 after bin 10 or so, and then .97 after bin 45, etc.

To obtain the required population per-stimulus time histogram from the total of the 3 sub-regions, we apply the formula:

$$S_k \approx \frac{I_k}{\sum_i \left[ G_{k,i} \alpha_i \right]}$$

So, to do the calculation:

1. Assume that before time 0 there has been no significant amount of firing. (If a previous token was coded earlier, then the processor will remember the $I_k$'s from that token, and how long ago).

2. Loop over each pulse, or 'k'.

3. Calculate $G_{k,i}$ as described above.

4. Using the equation above, calculate the required $S_k$. Also, store the three $I_{k,i}$ values this will evoke for use in calculations of future $G_{k,i}$ values.

5. Using the lookup table (as previously discussed) determine the required intensity of the pulse.

6. Administer the pulse for the correct amount of time, and go to step 2.

This procedure is readily implementable using conventional software techniques.

Variations and alternatives are possible within the general scope of this invention, as will be apparent to the reader. In particular, it is noted that the various processing components may be differently arranged, so that for example some or all the look up tables are located within the implanted portion of the device.

## CLAIMS

1. An auditory prosthesis, comprising processing means for receiving an electrical signal corresponding to an acoustic signal, and stimulation means adapted to provide electrical stimuli to the cochlea of a human, said stimulation means including an electrode array comprising a plurality of electrodes operatively located within the cochlea, said device being arranged so as to permit selected electrodes to be provided with stimuli, said stimulation means being responsive to control signals received from said processing means,

characterised in that said processing means processes said electrical signals in accordance with a predetermined instruction set, said instruction set determining the stimulation to be applied in response to the acoustic signal including the electrodes to be stimulated, the amplitude of the stimuli, and the timing of the stimuli, said processing means providing control signals to said stimulation means to cause said stimulation means to produce a set of stimuli, said set including for at least one electrode a first stimulus pulse and at least one further pulse within the relative refractory period of at least a substantial number of the nerve fibres stimulated by said first pulse, the set being selected such that the neural structures of a patient in response to said set have a time domain response which is an approximation to the time domain response of a normal hearing person to said acoustic signal.

2. An auditory prosthesis according to claim 1, wherein said instruction set includes means for analysing said electrical signal and determining which of a predefined group of acoustic features a portion of the electrical signal corresponds to, and a look-up table referenced to ones of said group containing control signals corresponding to sets of stimuli, so that the stimuli required to be presented for a given electrical signal can be determined by successive steps of analysis of said electrical signal, and obtaining the appropriate control signals corresponding to sets of stimuli from said look up table.

3. An auditory prosthesis according to claim 1 or claim 2, wherein said

signal is analysed within a plurality of frequency channels, and for each channel a separate analysis is performed corresponding to approximating the time domain response of part of the neural structures corresponding to that population of the nerve fibres most responsive to the frequency channel.

4. An auditory prosthesis according to claim 1, wherein the received acoustic signal is processed using a model of neural response to determine an approximation of the time domain response of a normal hearing person to a sample of said acoustic signal, said approximation being used to derive the desired stimulus amplitude.

5. An auditory prosthesis according to claim 4, wherein said amplitude is determined by calculating a desired stimulus function for the patient corresponding to the approximation of the time domain response of a normal hearing person, and thereby deriving the desired stimulus amplitude.

6. An auditory prosthesis according to claim 4, wherein said desired stimulus function is related to said desired stimulus amplitude using a look-up table.

7. An auditory prosthesis according to claim 1, wherein for each stimulated electrode, the stimulus set comprises multiple pulses presented at a rate much faster than the relative refractory period of the associated neurons.

8. An auditory prosthesis according to claim 7, wherein the stimulus set is chosen for each electrode such that the adjacent neurons exhibit a per-stimulus time histogram which is an approximation to the per-stimulus time histogram generated by a corresponding acoustic stimulus in a normal hearing person.

9. An auditory prosthesis according to claim 8, wherein said instruction set determines the sets of stimuli for each stimulating electrode in accordance with one or more selected from the set comprising a model of neural response, pre-

determined patient response data, and telemetry from said stimulating means.

10. An auditory prosthesis according to any one of claims 7 to 9, wherein at least some of the stimulus sets are chosen so as to excite different population bands of neurons.

11. An auditory prosthesis according to claim 10, wherein the size of the population bands is chosen in accordance with experimentally derived patient data in order to maximise the naturalness of the perception of sound by patients.

12. An auditory prosthesis according to claim 11, wherein the size of the bands is customised for each patient.

13. A method for determining sets of stimuli to be applied to selected electrodes in an auditory prosthesis, said prosthesis being of the type comprising processing means for receiving an electrical signal corresponding to an acoustic signal, and stimulation means adapted to provide electrical stimuli to the cochlea of a human, said stimulation means including an electrode array comprising a plurality of electrodes operatively located within the cochlea, said device being arranged so as to permit selected electrodes to be provided with stimuli, said stimulation means being responsive to control signals received from said processing means,

said method comprising processing said electrical signals in accordance with a predetermined instruction set , said instruction set performing the steps of:

analysing the electrical signal to determine the electrodes to be stimulated;

for each electrode to be stimulated, determining a set of stimuli so that the neural structures of a patient responsive to each electrode in response to said set of stimuli have a time domain response which is an approximation to the time domain response of a normal hearing person to said acoustic signal, said stimulus set including at least the amplitude of the stimuli, and the timing of the stimuli, and

providing control signals to said stimulation means to cause said

stimulation means to produce said sets of stimuli.

14. A method according to claim 13, wherein said analysis step further comprises determining which of a predefined group of acoustic features a portion of the electrical signal corresponds to, and a look-up table referenced to ones of said group containing corresponding sets of stimuli, so that the stimuli required to be presented for a given electrical signal can be determined by successive steps of analysis of said electrical signal, and obtaining the appropriate control signals corresponding to sets of stimuli from said look up table.

15. A method according to claim 13 or claim 14, wherein said signal is analysed within a plurality of frequency channels, and for each channel a separate analysis is performed corresponding to approximating the time domain response of part of the neural structures corresponding to that population of the nerve fibres most responsive to the frequency channel.

16. A method according to claim 15, wherein said determining step is performed using a model of neural response to determine an approximation of the time domain response of a normal hearing person to a sample of said acoustic signal, said approximation being used to derive the desired stimulus amplitude.

17. A method according to claim 16, wherein said amplitude is determined by calculating a desired stimulus function for the patient corresponding to the approximation of the time domain response of a normal hearing person, and thereby deriving the desired stimulus amplitude.

18. A method according to claim 16, wherein said desired stimulus function is related to said desired stimulus amplitude using a look-up table.

19. A method according to claim 13, wherein for each stimulated electrode, the set of stimuli comprises multiple pulses presented at a rate much faster than

the relative refractory period of the associated neurons.

20. A method according to claim 19, wherein the stimulus set is chosen for each electrode such that the adjacent neurons exhibit a per-stimulus time histogram which is an approximation to the per-stimulus time histogram generated by a corresponding acoustic stimulus in a normal hearing person.

21. A method according to claim 20, wherein said instruction set determines the sets of stimuli for each stimulating electrode in accordance with one or more techniques selected from the set comprising a model of neural response, pre-determined patient response data, and telemetry from said stimulating means.

22. A method according to any one of claims 19 to 21, wherein at least some of the stimulus sets are chosen so as to excite different population bands of neurons.

23. A method according to claim 22, wherein the size of the population bands is chosen in accordance with experimentally derived patient data in order to maximise the perception of sound by patients.

24. A method according to claim 23, wherein the size of the bands is customised for each patient.

Fig 1.

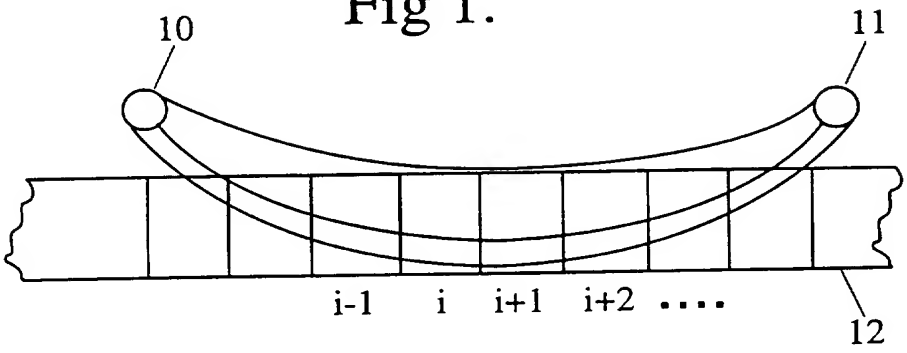

10
11
i-1
i
i+1
i+2
....
12

Fig 2.

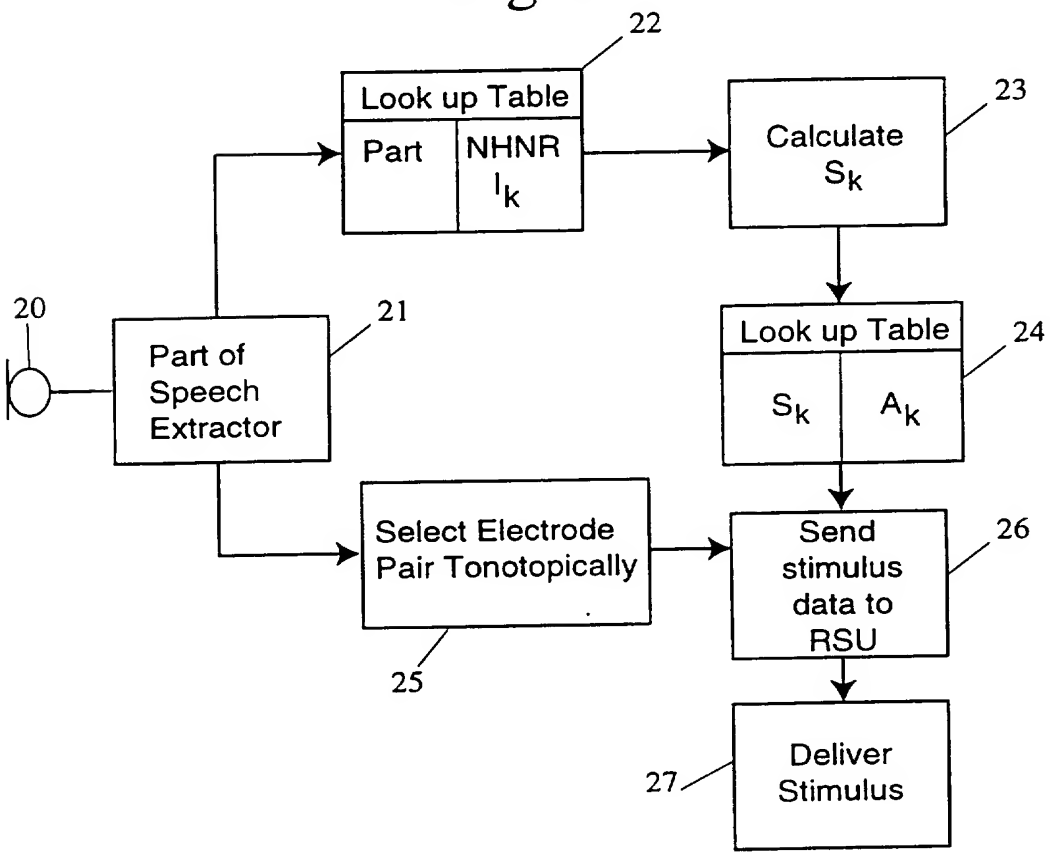

22
Look up Table
Part
NHNR
$I_k$
23
Calculate
$S_k$
20
21
Part of
Speech
Extractor
Look up Table
24
$S_k$
$A_k$
Select Electrode
Pair Tonotopically
25
Send
stimulus
data to
RSU
26
Deliver
Stimulus
27

Fig 3.

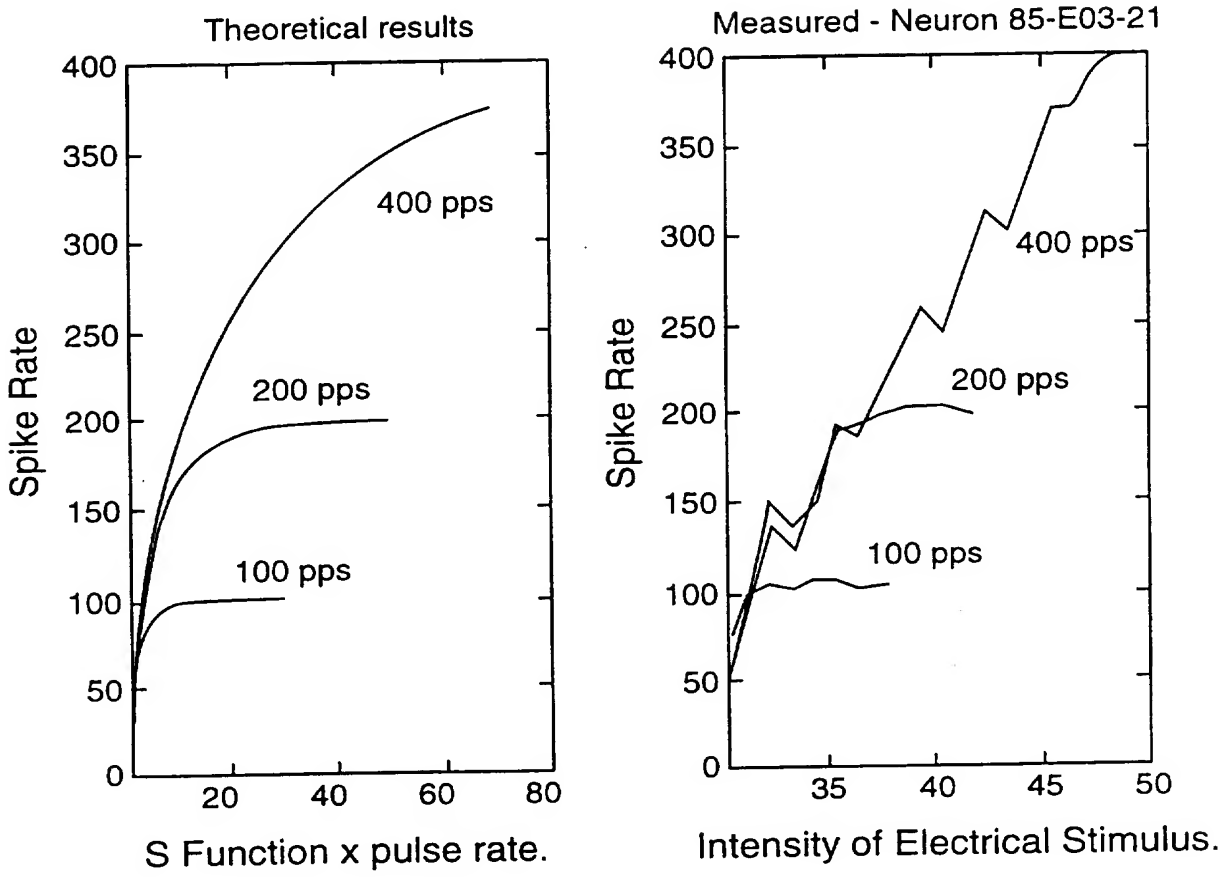

Theoretical results
Spike Rate
400
350
300
250
200
150
100
50
0
20
40
60
80
400 pps
200 pps
100 pps
S Function x pulse rate.
Measured - Neuron 85-E03-21
Spike Rate
400
350
300
250
200
150
100
50
0
35
40
45
50
400 pps
200 pps
100 pps
Intensity of Electrical Stimulus.

Fig 4.

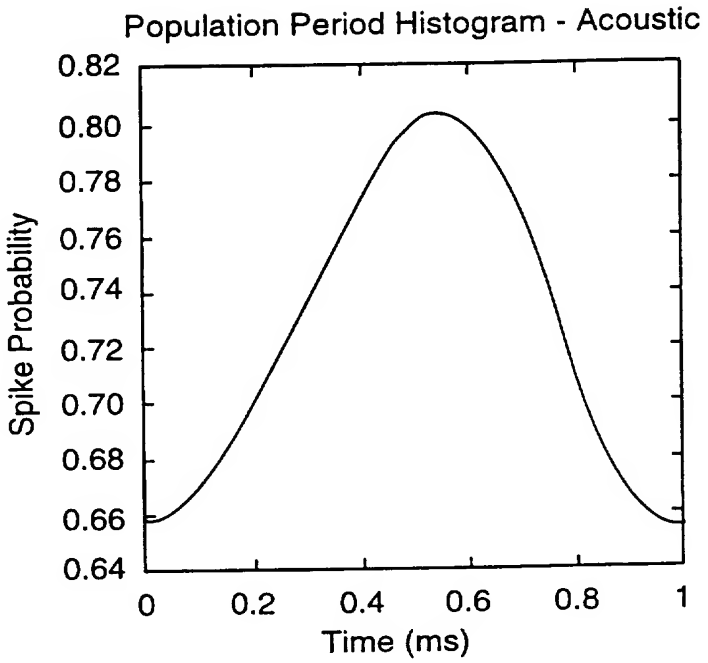

Population Period Histogram - Acoustic
Spike Probability
0.82
0.80
0.78
0.76
0.74
0.72
0.70
0.68
0.66
0.64
0
0.2
0.4
0.6
0.8
1
Time (ms)

Fig 5.

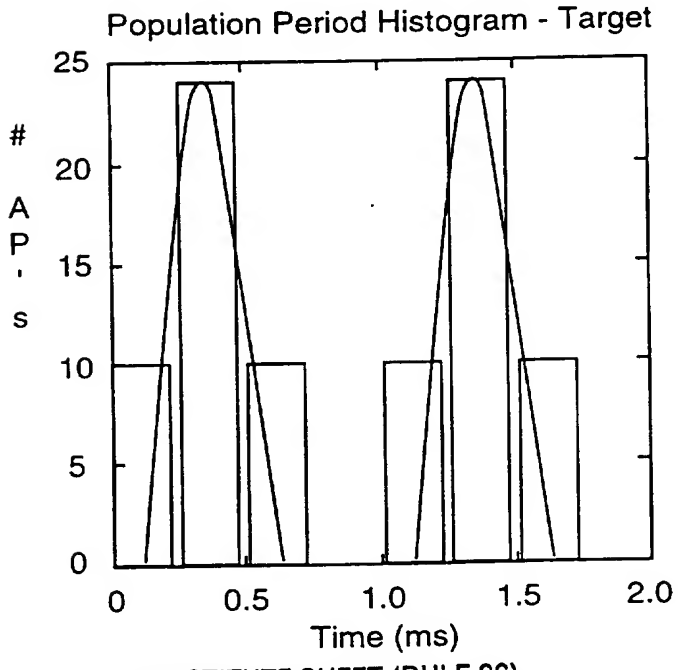

Population Period Histogram - Target
# A P - s
25
20
15
10
5
0
0
0.5
1.0
1.5
2.0
Time (ms)

Fig 6.

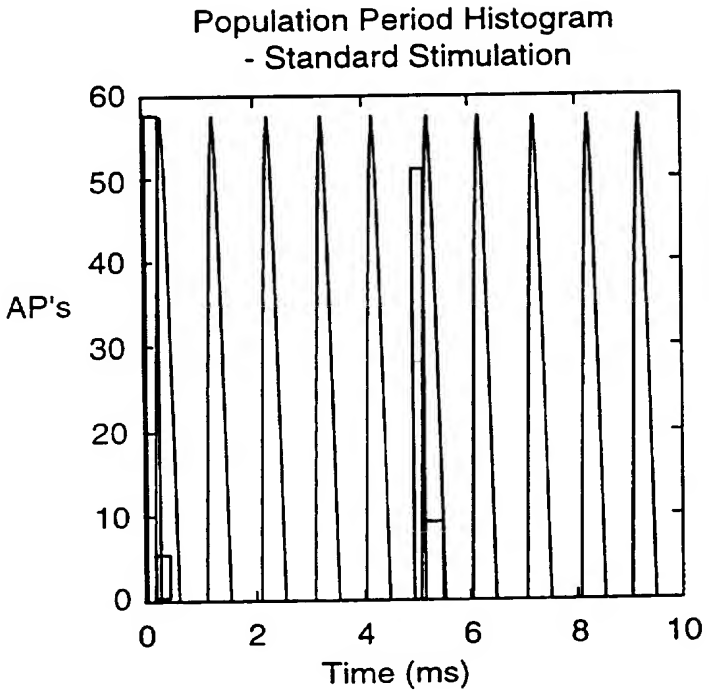

Population Period Histogram
- Standard Stimulation
AP's
60
50
40
30
20
10
0
0
2
4
6
8
10
Time (ms)

Fig 7.

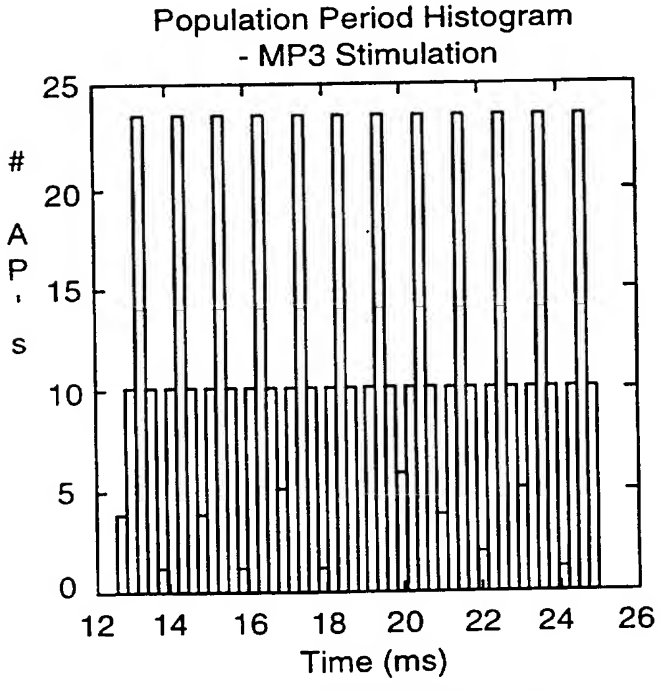

Population Period Histogram
- MP3 Stimulation
# APs
25
20
15
10
5
0
12
14
16
18
20
22
24
26
Time (ms)

Fig 8.

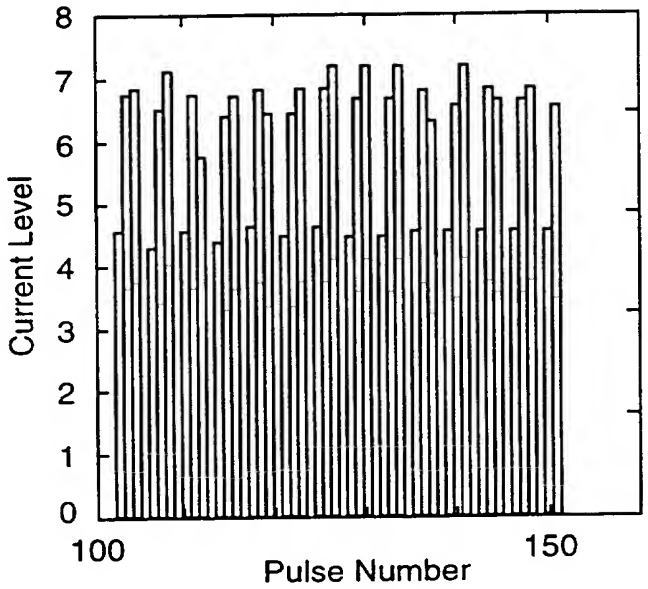

8
7
6
5
4
3
2
1
0
Current Level
100
150
Pulse Number

Fig 9.

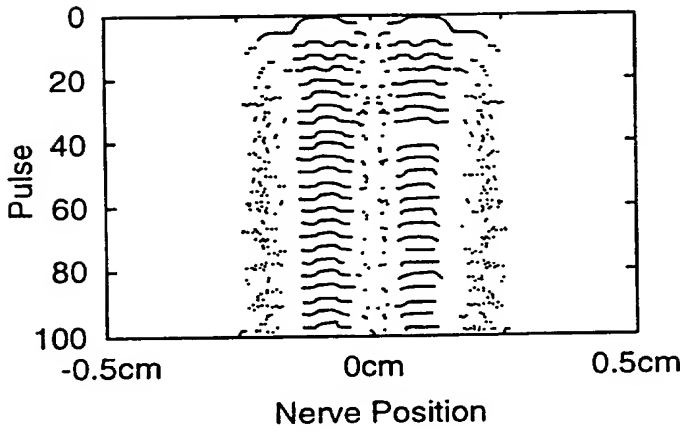

0
20
40
60
80
100
Pulse
-0.5cm
0cm
0.5cm
Nerve Position

Fig 10.

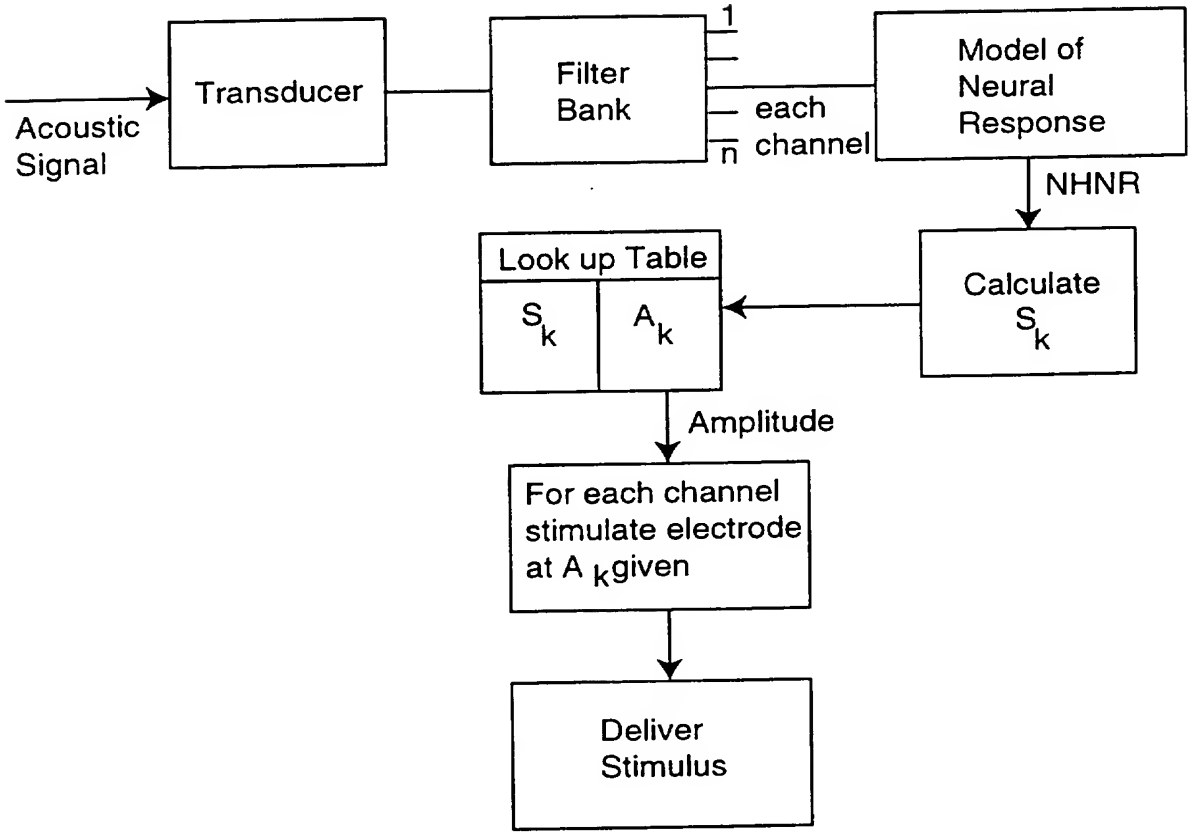

Acoustic Signal
Transducer
Filter Bank
1
each channel
n
Model of Neural Response
NHNR
Calculate $S_k$
Look up Table
$S_k$
$A_k$
Amplitude
For each channel stimulate electrode at $A_k$ given
Deliver Stimulus

Fig 11.

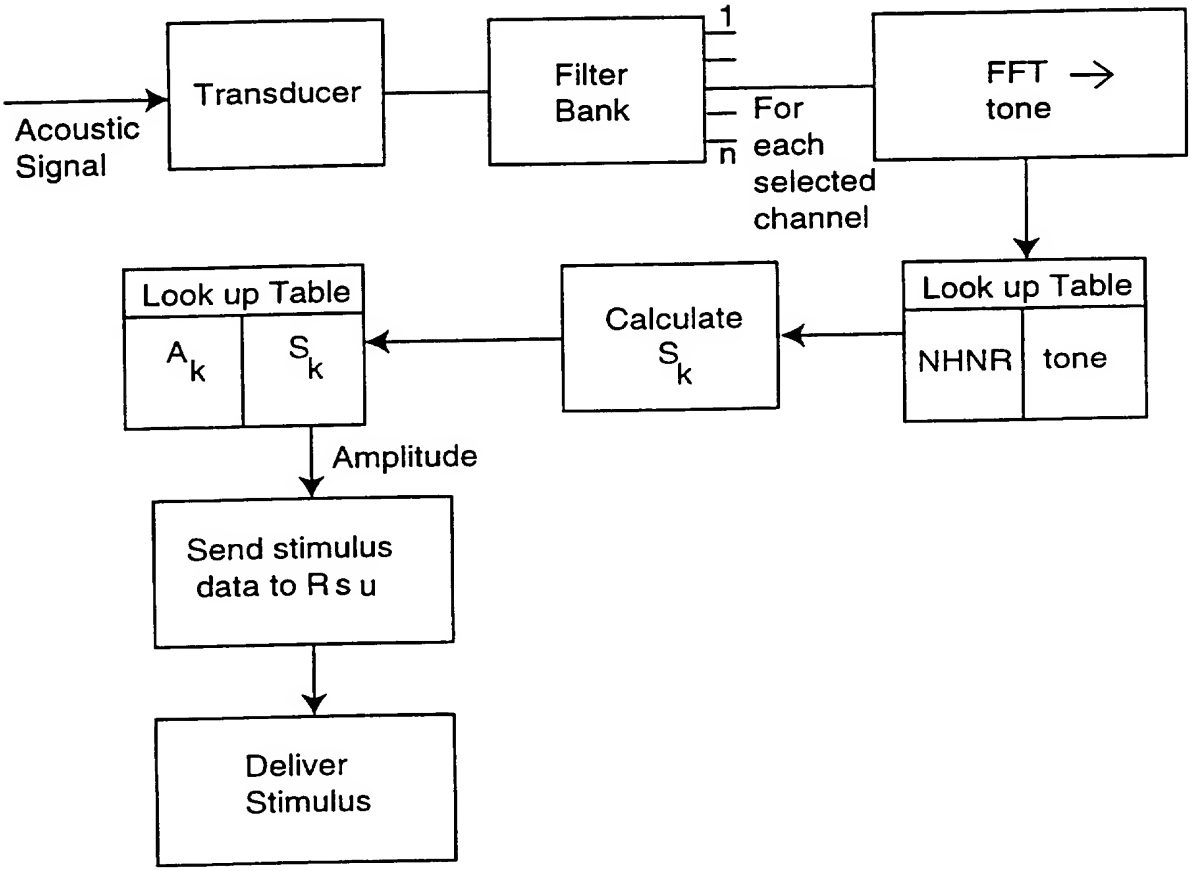
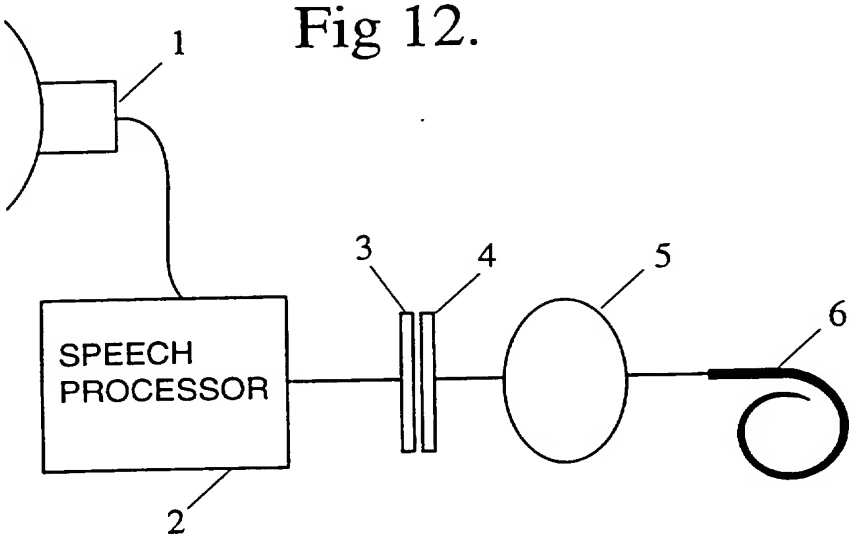
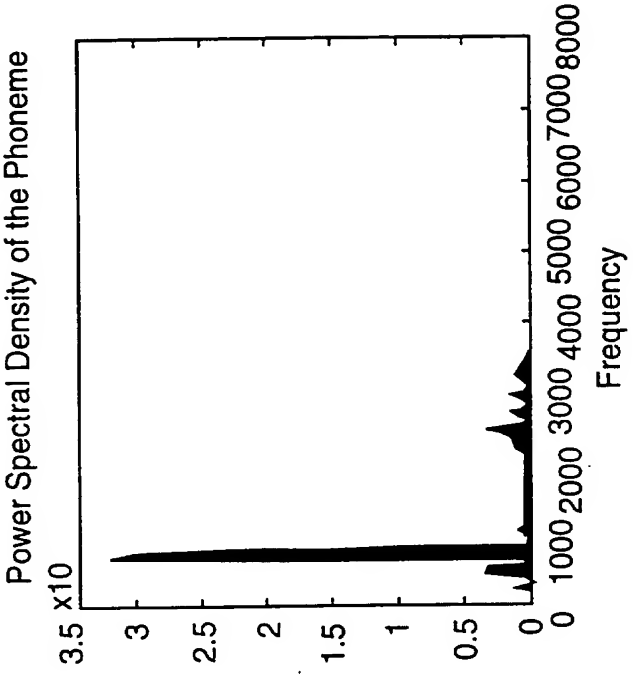

Acoustic Signal
Transducer
Filter Bank
1
n
For each selected channel
FFT → tone
Look up Table
NHNR
tone
Calculate $S_k$
Look up Table
$A_k$
$S_k$
Amplitude
Send stimulus data to R s u
Deliver Stimulus

Fig 12.


1
SPEECH PROCESSOR
2
3
4
5
6


Power Spectral Density of the Phoneme
x10
3.5
3
2.5
2
1.5
1
0.5
0
0 1000 2000 3000 4000 5000 6000 7000 8000
Frequency

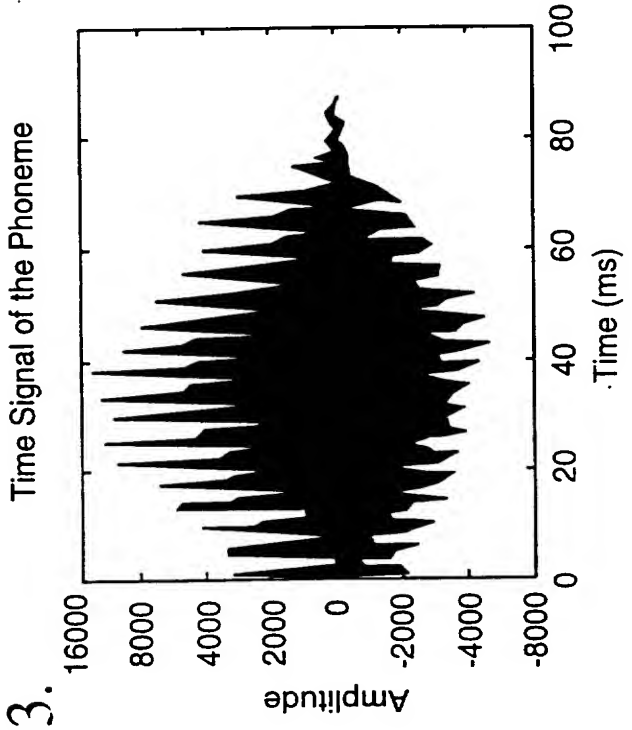
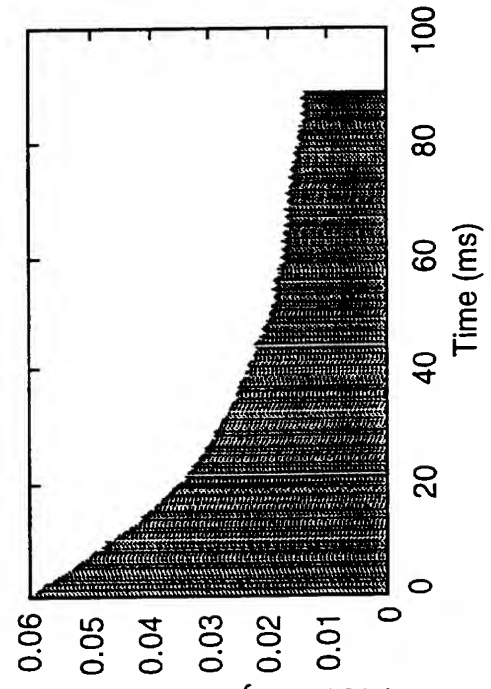

Time Signal of the Phoneme
Amplitude
16000
8000
4000
2000
0
-2000
-4000
-8000
0 20 40 60 80 100
Time (ms)

Fig 13.


Average Neural Firing
Probability-Band 1 of 20
0.06
0.05
0.04
0.03
0.02
0.01
0
0 20 40 60 80 100
Time (ms)

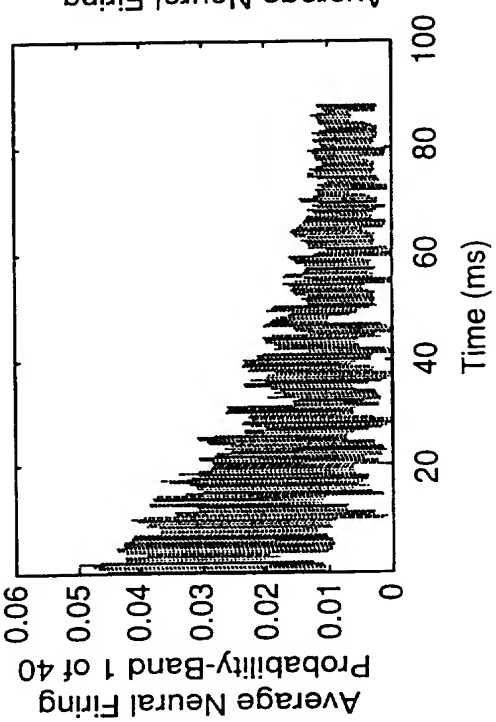

Average Neural Firing
Probability-Band 1 of 40
0.06
0.05
0.04
0.03
0.02
0.01
0
0 20 40 60 80 100
Time (ms)

Fig 14.

Fig 15.

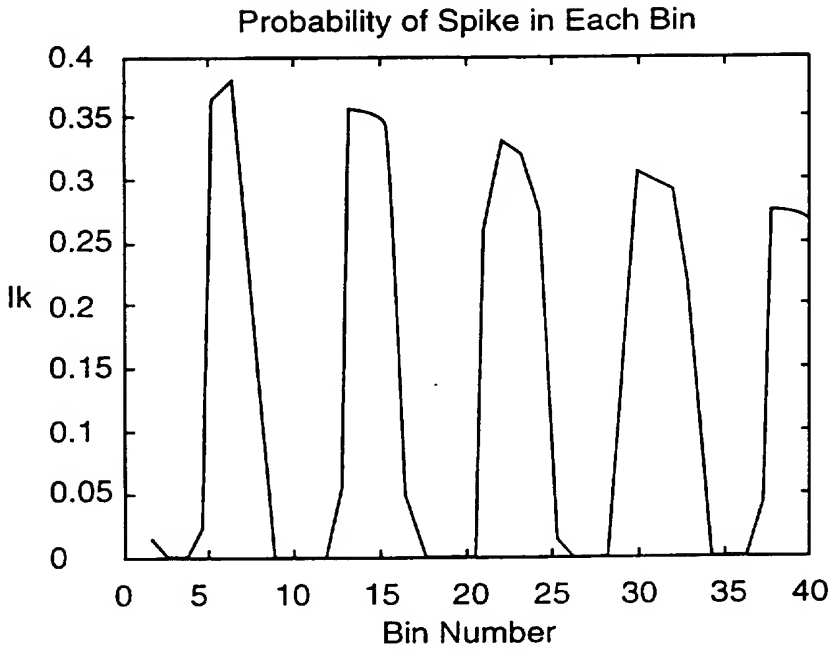
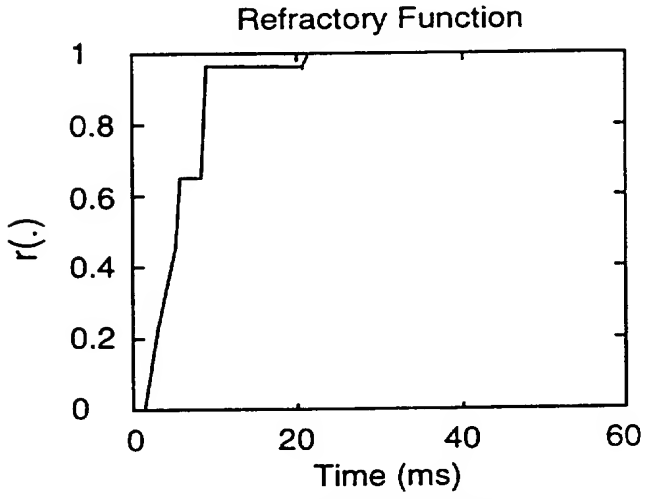

Probability of Spike in Each Bin
0.4
0.35
0.3
0.25
Ik 0.2
0.15
0.1
0.05
0
0 5 10 15 20 25 30 35 40
Bin Number

Fig 16


Refractory Function
1
0.8
0.6
r(.) 0.4
0.2
0
0 20 40 60
Time (ms)

# INTERNATIONAL SEARCH REPORT

International Application No.
PCT/AU 95/00686

## A. CLASSIFICATION OF SUBJECT MATTER

Int Cl[6]: H04R 25/00 A61F 11/04

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC H04R 25/00 A61F 2/18 2/48 11/04

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
AU: IPC as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
DERWENT
JAPIO

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No |
|---|---|---|
| | WO 9103913 A (COCHLEAR PTY LTD) 21 March 1991 | |
| X | See entire document | 13 |
| A | | 1-12, 14-24 |
| | US 4593696 A (HOCHMAIR ET AL) 10 June 1986 | |
| X | See entire document | 13 |
| A | | 1-12, 14-24 |
| | AU 46815/85 A (UNIVERSITY OF MELBOURNE) 13 March 1986 | |
| X | See entire document | 13 |
| A | | 1-12, 14-24 |

[X] Further documents are listed in the continuation of Box C

[X] See patent family annex

* Special categories of cited documents:

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 9 January 1996 | 19 January 1996 |

| Name and mailing address of the ISA/AU | Authorized officer |
|---|---|
| AUSTRALIAN INDUSTRIAL PROPERTY ORGANISATION<br>PO BOX 200<br>WODEN ACT 2606<br>AUSTRALIA Facsimile No.: (06) 285 3929 | A.K. GATELY<br>Telephone No.: (06) 283 2208 |

**INTERNATIONAL SEARCH REPORT**

International Application No.
**PCT/AU 95/00686**

**C (Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| | US 4408608 A (DALY ET AL) 11 October 1983 | |
| X | See entire document | 13 |
| A | | 1-12, 14-24 |
| | EP 54418 A (COMMONWEALTH OF AUSTRALIA) 23 June 1982 | |
| X | See entire document | 13 |
| A | | 1-12, 14-24 |

**INTERNATIONAL SEARCH REPORT**

Information on patent family members

International Application No.
**PCT/AU 95/00686**

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

| Patent Document Cited in Search Report | | Patent Family Member | | | | | |
|---|---|---|---|---|---|---|---|
| WO | 9103913 | AU | 63392/90 | CA | 2024845 | EP | 450004 |
| | | JP | 4502876 | US | 5271397 | | |
| US | 4593696 | AT | 44873 | AU | 577501 | BR | 8600156 |
| | | CA | 1247227 | CN | 1006361 | DE | 3664561 |
| | | EP | 190836 | JP | 3023062 | US | 4593696 |
| AU | 46815/85 | US | 4974844 | | | | |
| US | 4408608 | DE | 3227483 | FR | 2530474 | US | 4408608 |
| EP | 54418 | AU | 541258 | CA | 1189147 | DE | 3171951 |
| | | DK | 5498/81 | JP | 1005900 | US | 4515158 |

END OF ANNEX